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PAPERMAKING FACTORS THAT INFLUENCE THE STRENGTH OF LINERBOARD W--ETC(U)
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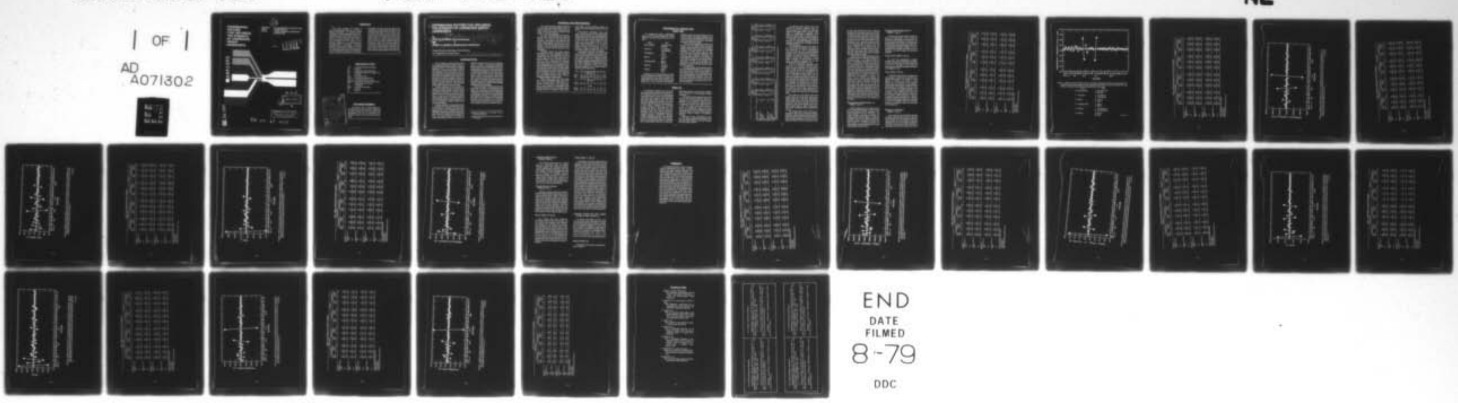

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PAPERMAKING FACTORS THAT INFLUENCE THE STRENGTH OF LINERBOARD WEIGHT HANDSHEETS

RESEARCH PAPER FPL 323

U.S. DEPARTMENT OF AGRICULTURE
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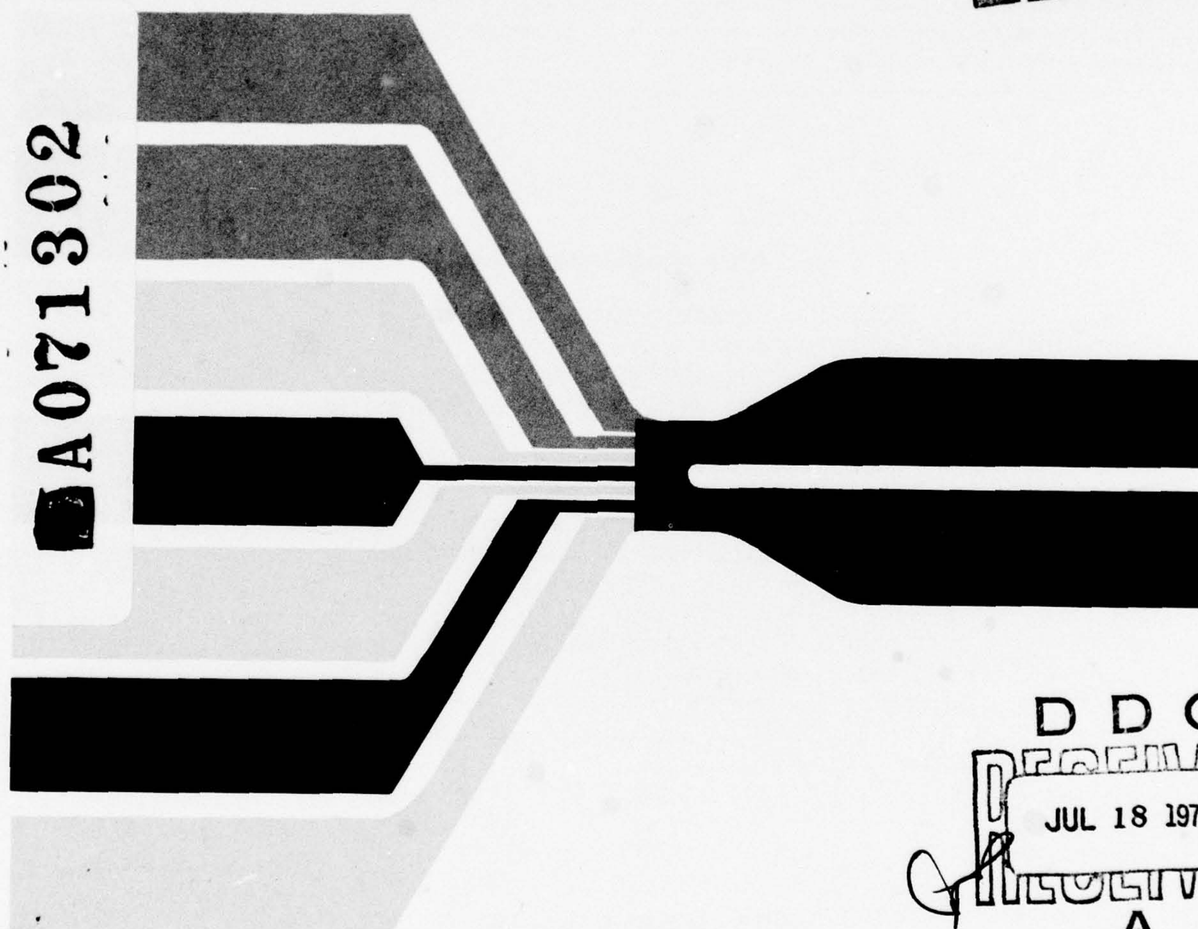

ABSTRACT

This study explores the effects of typical papermaking factors on a number of strength properties of linerboard weight handsheets. Several papermaking factors—wood species, pulp yield, type of refiner, consistency of pulp during refining, amount of refining, wet-press pressure, and surface—were evaluated for their effect on the strength properties of 42-pound-per-thousand-square-foot handsheets. Wet-press pressure, wood species, degree of refining, and yield were found to be the most important. The degree and direction of change depend on the particular property. For example, increasing wet-press pressure significantly increased the compressive strength of the handsheets whereas the type of wood species had little effect. On the other hand, wood species had a significant effect on the tensile strain to failure while wet-press pressure did not. Considering all the properties in terms of end-use requirements, the handsheets made from low-yield southern pine pulp, refined at 3 percent consistency in a disk mill to 450 milliliters Canadian Standard freeness and formed using high wet-press pressure, gave the best overall results.

Abbreviations Used

CSF	=	Canadian Standard freeness
g	=	grams
g/cc	=	grams per cubic centimeter
ksi	=	thousand pounds per square inch
lb	=	*pounds*
lb/in.	=	pounds per inch
lb/in.^{2}	=	pounds per square inch
lb/in. w	=	pounds per inch of width
lb/M ft^2	=	pounds per thousand square feet
mil	=	thousandths of an inch
ml	=	milliliters
MOE	=	modulus of elasticity
pct	=	percent
pt	=	points

ACKNOWLEDGMENT

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PAPERMAKING FACTORS THAT INFLUENCE THE STRENGTH OF LINERBOARD WEIGHT HANDSHEETS

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INTRODUCTION

Burst strength and basis weight are the two material properties of major concern in the manufacture of linerboard for corrugated fiberboard. This is true primarily because these are the properties specified in the carrier regulations. Thus, the industry over the years has selected methods and techniques that produce linerboards which meet the requirements of burst and weight. However, it has been found that a container can have the proper burst and weight as required by the carrier regulations but still not necessarily perform well in the service environment.

Greater emphasis is being placed on design of containers today to meet the specific end-use requirements of actual service conditions. Thus, there is a need to understand what can be done with existing equipment to improve the linerboard properties which actually relate to the performance of containers exposed to actual service conditions. Compressive strength properties are of particular interest.

A major difficulty in solving this problem is that the actual service environment is not fully defined or understood. Consequently, adequate data are not available as to what paperboard properties are really essential or what minimum strength levels are required. Thus, this study explores the effects of typical papermaking factors on a number of strength properties that may be important, using nominal 42-pound-per-thousand-square-foot (lb/M ft^2) handsheets made with varying types of fiber and varying types of papermaking equipment. To accomplish this, a statistically designed study was undertaken to evaluate the various papermaking factors such as wood species, pulp yield, type of refining, consistency at time of refining, degree of refining, wet-press pressure, and surface (varied by pressing the wet sheet against a blotter or a wire) on the strength properties of the handsheets.

Another objective of this study is to help determine the effect of substituting other fibers such as hardwood on the properties of linerboard, and to determine the interaction of these fibers with some of the controllable papermaking operations. It is recognized that the results do not address the curvilinear response of some factors or the possibility that a change in the level of one of the factors could have a different significant effect.

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[1] Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

[2] Numbers in parentheses refer to literature cited at end of this report.

MATERIAL AND PROCEDURES

Two species of wood, southern pine and red oak, were selected because of the inherent difference in fiber morphology between the two, particularly in terms of fiber length and cell wall thickness.

The wood was debarked and chipped to provide 5/8-in. chips for pulping by the kraft process. The southern pine and red oak chips were each pulped to two different yield levels, approximately 50 and 60 pct. The details of the pulping conditions are shown in table 1. The hot, softened chips were then fiberized in a disk mill and diluted to 3 pct consistency.

Individual cooks of the same species were blended in a tank, dewatered to 25 pct consistency, and then separated into three different batches. One batch was diluted to approximately 18 pct consistency and refined in a 36-in. double-disk mill equipped with plates with no retaining rings. Another batch was diluted to 3 pct consistency with room temperature water and passed through the same disk refiner with the same plates, and the remaining one-third was diluted to 3 pct and refined in a conical refiner equipped with a hydrating tackle. In each case, the pulp was refined to 450-ml and to 600-ml Canadian Standard freeness (CSF).

These refined pulps were then made into 7- by 9-in. handsheets using a sheetmold with a 150-mesh screen. There was no circulation of white water, no pH adjustment, size, or alum added. The handsheets were couched off the mold with blotters, placed between blotters or between a blotter and a fine screen, and then placed in stacks of three or four and pressed at either 40 or 160 lb/in.^{2}

Wet-pressed handsheets were then dried using one drier of the experimental paper machine. Each sheet was fed between the drier and drier felt, with the sheet reversed after each pass. This process was continued until the moisture content of the sheet was approximately 6 pct. The handsheets were conditioned at 73° F, 50 pct relative humidity, and evaluated for burst, thickness, weight, density, tear, fold, and ring crush according to TAPPI standards.

Compressive strength was determined using the device developed by Jackson (*2*)[2] and the tensile stress-strain properties, maximum stress, modulus of elasticity (MOE), and strain-to-failure, were determined using the method suggested by Setterholm (*7*) and modified by Jewett (*3*). Handsheet thickness was also determined using the stylus method developed at the Forest Products Laboratory by Setterholm (*8*).

Table 1.—Pulping conditions for southern pine and red oak (sulfidity 25 pct)

Digestion number	NaOH (Na_2O)	Na_2S (Na_2O)	Active alkali	Liquor/ wood	Time to 170° C	Time at 170° C	Yield	Kappa number
	Pct	Pct	Pct		Min.	Min.	Pct	
				SOUTHERN PINE				
14-4543-6	12.0	4.0	16.0	4/1	90	75	49.3	52.7
14-4547-50	10.875	3.625	14.5	4/1	90	30	60.2	118.0
				RED OAK				
14-4551-4	12.75	4.25	17.0	3.5/1	60	60	50.8	17.4
14-4560-3	9.0	3.0	12.0	3.5/1	60	15	60.9	74.0

EXPERIMENTAL DESIGN AND ANALYSIS

To evaluate the various papermaking factors, a 2^7 full factorial design was initially planned. The factors and levels are as follows:

Factor	*Level*
Wood species	Southern pine Red oak
Pulp yield	Low (50 pct) High (60 pct)
Consistency	3 pct 18 pct
Refiner	Conical Disk
Freeness (CSF)	450 ml 600 ml
Pressure	40 lb/in.^{2} 160 lb/in.^{2}
Surface	Blotter Wire

Because of the large quantity of data and the problems with coding, an analysis-of-means approach was used to analyze the data based on the work by Schilling (*5, 6*) and Nelson (*4*) in which the mean and standard deviation values were used instead of the individual values. This greatly speeded up the coding work and still allowed for the evaluation of the significant effects of the various parameters that were studied.

The results are presented in tabular and graphic form. The graphs show the actual change in the properties by factors through a plotting program that allows for immediate indication of those factors that are both statistically and practically significant, their level, and their numerical difference. The numerical data are based on the average of 10 replications except for the tensile properties which are based on the average of six replications. All the data have been standardized to a 42-lb handsheet weight to make direct comparisons.

In analyzing each of the material properties, the response difference for the levels of each factor had to exceed 10 pct, based on the overall average, to be considered practically significant, and in addition that 10 pct had to be statistically significant at the 1 pct level. With this as the criterion, each of the material properties was analyzed for the effect of the factors.

RESULTS

As expected, freeness was one factor that significantly affected all properties of the linerboard except for tear, and generally in a positive manner—that is, the handsheets made with pulp at 450 ml CSF were better than those made at 600 ml CSF. The other factor that significantly affected many of the strength properties was wet-press pressure. In this study, increasing the wet-press pressure resulted in improvements in the compressive, tensile, ring crush, and burst strengths, MOE, and folding endurance. Thickness, of course, was decreased with increased pressure. Increasing wet-press pressure generally resulted in the reduction of tear for handsheets made with southern pine pulp but had little effect or increased tear for handsheets made with red oak pulp. Wet-press pressure was the single biggest factor affecting the compressive strength properties.

As expected, wood species was a major factor in the strength properties. However, it depended on the particular species as to whether it was a positive or negative effect; for example, in general there was a reduction in tear, fold, burst, and tensile strain to failure for handsheets made with short fibers. On the other hand, the MOE increased using short fibers, and type of fiber was not a significant factor in terms of compressive strength.

Results of these combinations along with the highest properties obtained for the particular wood species, yield, and freeness group are given in table 2.

Table 2.—Papermaking factor combinations resulting in handsheets with high properties[1]

	[2]SPH 600		[2]SPH 450		[2]SPL 600		[2]SPL 450		[2]OH 600		[2]OH 450		[2]OL 450	
	Disk, 18 pct, 160 lb/in.² wire		Disk, 18 pct, 160 lb/in.² wire		Disk, 18 pct, 160 lb/in.² wire		Disk, 3 pct, 160 lb/in.² wire		Conical, 3 pct, 160 lb/in.² wire		Disk, 20 pct, 160 lb/in.² wire		Disk, 3 pct, 160 lb/in.² blotter	
Compressive strength .... lb/in. w	29.4	(29.4)	30.5	(31.4)	30.6	(30.6)	30.2	(32.4)	27.6	(27.6)	32.4	(33.7)	31.6	(31.6)
Tear .... g	300	(347)	304	(347)	344	(419)	339	(402)	167	(167)	196	(200)	244	(244)
Modulus of elasticity .... ksi	432	(436)	517	(517)	550	(550)	598	(598)	559	(559)	670	(735)	650	(800)
Tensile strength .... lb/in.²	5,630	(5,630)	6,660	(6,660)	8,120	(8,120)	8,740	(8,740)	5,280	(5,280)	7,570	(7,570)	6,330	(7,230)
Tensile strain .... pct	8.9	(8.9)	10.8	(10.8)	9.5	(9.5)	9.4	(11.6)	5.1	(5.1)	6.8	(6.8)	5.1	(5.3)
Burst .... pt	164	(164)	172	(172)	207	(207)	221	(227)	118	(118)	162	(162)	128	(155)
Folds	1,276	(1,276)	1,180	(1,180)	3,390	(3,390)	2,934	(2,930)	574	(574)	1,857	(1,857)	139	(469)
Compressive strength .... lb/in.²	2,720	(2,720)	3,000	(3,030)	3,140	(3,140)	3,270	(3,550)	2,550	(2,550)	3,180	(3,340)	2,890	(2,990)
Ring crush .... lb	125.3	(125.9)	119.2	(133.5)	118.3	(132.1)	121.7	(135.4)	114.4	(119.9)	126.5	(136.6)	122.2	(124.3)
Thickness (TAPPI) .... mil	11.6	(16.7)	11.4	(14.9)	10.6	(16.5)	10.5	(13.7)	12.4	(16.4)	11.9	(14.4)	11.5	(15.2)
Thickness(FPL) .... mil	10.8	(15.8)	10.2	(14.1)	9.8	(14.7)	9.2	(12.9)	10.9	(15.4)	10.1	(13.2)	11.0	(13.9)
Density .... g/cc	.70	(.70)	.71	(.71)	.76	(.76)	.77	(.80)	.65	(.65)	.68	(.70)	.70	(.73)

[1] Numbers in parentheses are highest property value for each species, yield, and freeness group.

[2] SPH is southern pine, high yield; SPL is southern pine, low yield; OH is oak, high yield; OL is oak, low yield. Number following the abbreviation is Canadian Standard freeness in ml.

In analyzing all the results, there were virtually no surprises regarding major effects, although the influence of wet-press pressure was greater than expected, especially on compressive properties. Compressive strength was not significantly affected by yield; however, previous research (*1*) indicated that edgewise compressive strength of corrugated fiberboard may be adversely affected if the corrugated is made from high-yield pulp.

As indicated previously, one object of this work is to help determine the effect of the interaction of various papermaking operations and fibers on a given linerboard property. Thus, the tables are organized to facilitate the making of these comparisons. Specific results are presented in these tables, one table for each property, so that direct comparison between any of the variables can be made (tables 3 to 14).

Thus, if a linerboard is presently made using 100 pct, low-yield, southern pine—refined at 3 pct consistency in a double disk refiner to 600 ml CSF and wet-pressed with low pressure—and if it is desirable to improve compressive strength, table 3 can be used. In this table, the value 24.3 lb/in. for this set of operating conditions is found, and this value can be compared with the results of any change in operation that is of interest. For example, by increasing the wet-press pressure, the compressive strength went to 28.9; reducing the freeness and increasing the pressure, it went to 29.5. Likewise, one can get an estimate of what happens with a major change like switching to hardwood fiber.

The levels of the factors that were studied were met except that there was a slight difference in the high consistency refining level—that is, 18 pct for the southern pine and 20 pct for the red oak—and in the variation in CSF which ranged from 430 to 460 and 580 to 625 ml. Both of these variations were considered within experimental control.

The original intent was to conduct experiments using the full factorial design. However, it was not possible to refine pulp at high consistency with the conical refiner so the data were analyzed in terms of the two types of refiners—at 3 pct consistency over

all the other factors and then a separate analysis with the double disk at 3 and 18 pct consistency. Since the results were similar, only the statistical analysis for the two types of refiners is included. Also, the low-yield, red oak pulp had a CSF below 600 ml after fiberizing. Thus, it was not refined, and the same values are listed under both the 3 and 18 pct consistencies for each of the two types of refiners. It was decided that this data was a better estimate of actual properties than were values which could be calculated by a statistical missing value program using the other actual data.

The analysis of means results are given in a series of plots of property response versus factors (figs. 1 to 11). Each plot has the factor or interaction identified in terms of a letter or combination of letters (for instance, W—wood species, WY—wood species-yield interactions), direction of the effect, magnitude, and whether it is statistically significant. The small dashed lines on either side of the grand mean for the property are the 1 pct significance level for each of the factors or interactions. For example, in figure 1, the effect of wood species falls outside the dashed lines and is therefore statistically significant. However, because the practical effect was less than 10 pct it was not discussed further. Each plot contains all the main effects, two level interactions, and any significant three-level interactions. The nonsignificant three-level interactions and all higher-order interactions are not plotted. The darkened circles indicate practical significant effects (more than 10 pct). The ones of particular importance from the analysis are as follows:

Compressive Strength (lb/in. w) (Table 3, Fig. 1)

Results indicate that two major factors affect compressive strength: wet-press pressure and freeness. With an increase in wet-press pressure from 40 to 160 lb/in.^{2}, the overall average compressive strength increased 16 pct. With a reduction in freeness from 600 to 450 ml, the overall average compressive strength increased by 15 pct. No other factors or interactions affected the compressive strength significantly in terms of the arbitrary level of 10 pct.

Compressive Strength (lb/in.^{2}) (Table 4, Fig. 2)

These are the same values as given in table 3 but expressed in lb/in.^{2} using the thickness measurement as determined by the FPL stylus method (*8*). Two factors, wet-press pressure and freeness, are significant. Increasing the wet-press pressure resulted in a compressive strength increase of 41 pct. Reducing the freeness from 600 to 450 ml resulted in a 24 pct increase in compressive strength.

Ring Crush (Table 5, Fig. 3)

As with the compressive strength, freeness and wet-press pressure are significant factors. Reducing the freeness resulted in an 18 pct increase in ring crush and increasing the wet-press pressure resulted in an increase of 12 pct.

Tear (Table 6, Fig. 4)

Three factors significantly affected tear: wood species, yield, and the interaction of species and pressure. The effect of wood species is evident from figure 4, which shows a 61 pct reduction in tear between long (southern pine) and short (red oak) fibers as expected. The change in yield from 60 to 50 pct resulted in an average increase in tear of 18 pct. This is probably explained by the increase in fiber bonding with lower yield pulp. Since the species-pressure interaction is significant, further analysis is required. The data in table 6 indicates that, in general, increasing the pressure results in a decrease in tear for handsheets made with southern pine but an increase in tear for those made from red oak pulp.

Modulus of Elasticity (Table 7, Fig. 5)

Four major factors significantly affected the MOE—species, yield, freeness, and wet-press pressure. On the average, the MOE improved 40 pct with an increase in wet-press pressure, 30 pct with the species change to short-fiber red oak, 20 pct with reduction in freeness, and 14 pct with a reduction in yield.

Table 3.—Compressive strength (lb/in.) of 42-lb/M ft^2 handsheets[1]

	Southern pine kraft						Red oak kraft					
	Low yield (49.3 pct)			High yield (60.2 pct)			Low yield (50.8 pct)			High yield (60.9 pct)		
	Conical refiner	Double disk refiner		Conical refiner	Double disk refiner		Conical refiner	Double disk refiner		Conical refiner	Double disk refiner	
	[2]3	[2]3	[2]18	[2]3	[2]3	[2]18	[2]3	[2]3	[2]20	[2]3	[2]3	[2]20
450 Freeness[3]												
Low pressure (40 lb/in.^{2})												
Blotter	24.5 (0.89)	26.8 (1.13)	28.5 (1.31)	23.4 (1.10)	26.6 (0.88)	29.3 (0.42)	28.1 (0.71)	27.0 (0.72)	26.2 (1.23)	27.5 (0.52)	28.5 (1.37)	29.9 (1.15)
Wire	23.9 (1.46)	27.0 (0.81)	28.3 (0.91)	24.1 (0.82)	25.3 (1.28)	28.8 (1.33)	25.6 (0.85)	26.2 (1.37)	25.1 (2.42)	25.5 (2.40)	30.2 (1.69)	29.1 (0.81)
High pressure (160 lb/in.^{2})												
Blotter	28.7 (1.69)	29.5 (0.85)	30.9 (0.91)	29.4 (0.79)	30.1 (1.16)	31.4 (1.07)	30.8 (2.00)	31.6 (3.52)	28.9 (1.69)	31.6 (0.82)	32.4 (1.28)	33.7 (0.79)
Wire	28.7 (1.55)	30.2 (0.72)	32.4 (1.59)	30.4 (1.41)	29.1 (1.34)	30.5 (0.69)	30.8 (1.21)	30.7 (0.74)	30.5 (1.27)	30.9 (1.17)	31.9 (1.54)	32.4 (2.00)
600 Freeness[3]												
Low pressure (40 lb/in.^{2})												
Blotter	21.4 (0.83)	24.3 (1.43)	25.3 (0.61)	22.0 (0.61)	24.2 (0.92)	26.4 (0.87)	[4]21.9 (1.17)	[4]21.9 (1.17)	[4]21.9 (1.17)	24.3 (0.68)	21.0 (1.47)	21.5 (0.69)
Wire	21.0 (0.59)	23.3 (1.14)	26.3 (0.59)	22.5 (0.75)	23.2 (0.66)	24.5 (1.09)	[4]19.8 (1.30)	[4]19.8 (1.30)	[4]19.8 (1.30)	22.4 (0.46)	21.8 (0.66)	21.2 (0.99)
High pressure (160 lb/in.^{2})												
Blotter	26.3 (0.76)	28.9 (1.76)	29.2 (0.56)	25.9 (1.29)	26.2 (0.86)	27.8 (0.92)	[4]26.5 (1.47)	[4]26.5 (1.47)	[4]26.5 (1.47)	27.2 (0.68)	26.2 (0.90)	25.6 (0.76)
Wire	25.8 (0.31)	28.2 (0.96)	30.6 (0.91)	26.5 (1.36)	27.1 (2.45)	29.4 (0.99)	[4]24.8 (1.72)	[4]24.8 (1.72)	[4]24.8 (1.72)	27.6 (0.60)	26.2 (0.68)	25.4 (0.86)

[1] Numbers in parentheses are standard deviation.
[2] Percent consistency.
[3] Canadian Standard, ml.
[4] Pulps not refined (CSF was below 600 after fiberizing).

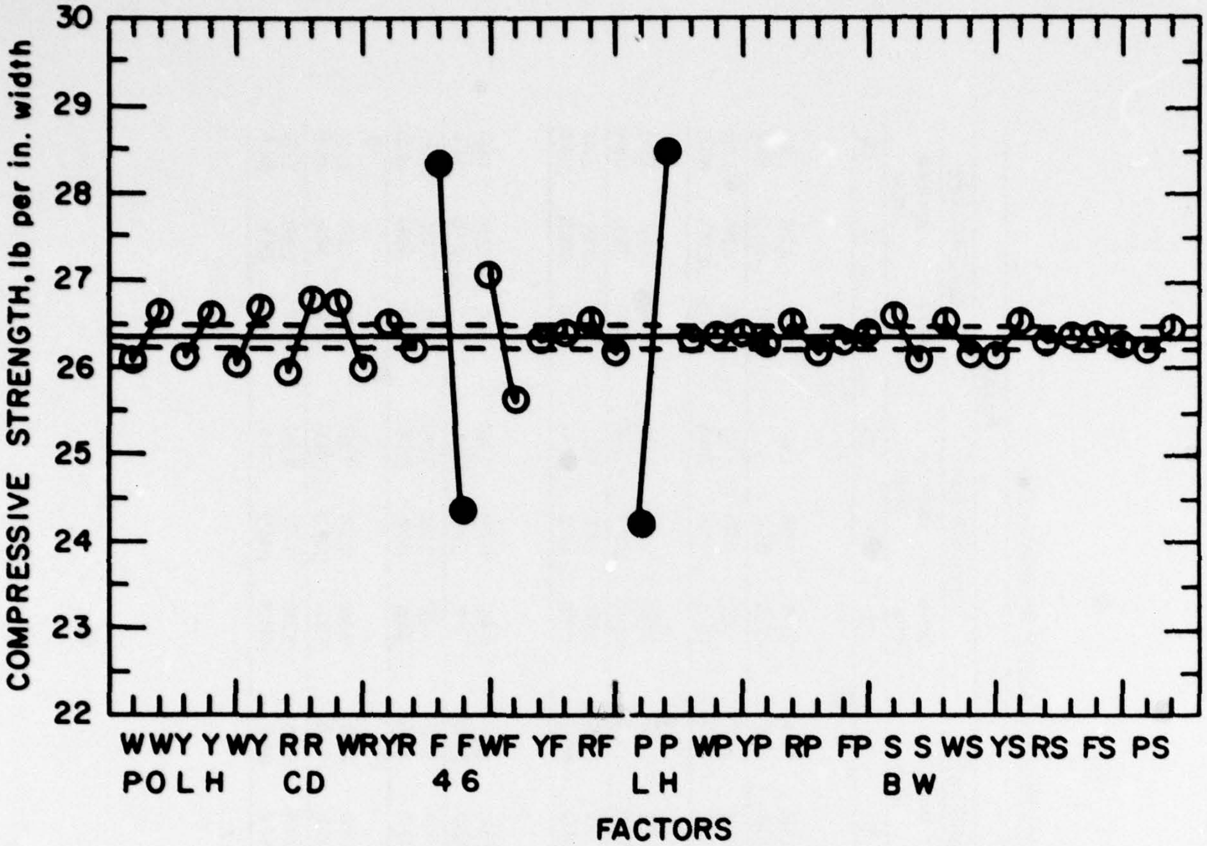

Figure 1.—Effect of various factors on the compressive strength of 42-lb/M ft² handsheets. The significant factors are freeness (F) and wet-press pressure (P) and are indicated by the filled symbols. Complete factor and level identification is as follows:

Factor		*Level*	
W	Wood species	P	Southern pine
		O	Red oak
Y	Pulp yield	L	Low (50 pct)
		H	High (60 pct)
R	Refiner	C	Conical
		D	Disk
F	Freeness (CSF)	4	450 ml
		6	600 ml
P	Pressure	L	Low (40 lb/in.²)
		H	High (160 lb/in.²)
S	Surface	B	Blotter
		W	Wire

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Table 4.—Compressive strength (lb/in.^{2}) of 42-lb/M ft^2 handsheets[1]

	Southern pine kraft						Red oak kraft					
	Low yield (49.3 pct)			High yield (60.2 pct)			Low yield (50.8 pct)			High yield (60.9 pct)		
	Conical refiner	Double disk refiner		Conical refiner	Double disk refiner		Conical refiner	Double disk refiner		Conical refiner	Double disk refiner	
	[2]3	[2]3	[2]18	[2]3	[2]3	[2]18	[2]3	[2]3	[2]20	[2]3	[2]3	[2]20
450 Freeness[3]												
Low pressure (40 lb/in.^{2})												
Blotter	1,950 (64.9)	2,290 (144.0)	2,800 (150.0)	1,680 (124.0)	1,920 (61.3)	2,410 (51.2)	2,070 (69.5)	1,950 (58.6)	1,920 (97.3)	2,130 (45.7)	2,200 (133.0)	2,370 (97.5)
Wire	1,860 (132.0)	2,340 (79.1)	2,730 (89.5)	1,810 (70.9)	1,820 (87.2)	2,460 (159.0)	1,910 (76.1)	1,920 (90.3)	1,860 (204.0)	2,050 (164.0)	2,280 (129.0)	2,350 (49.6)
High pressure (160 lb/in.^{2})												
Blotter	2,970 (231.0)	3,170 (121.0)	3,550 (100.0)	2,680 (130.0)	2,670 (91.4)	3,030 (117.0)	2,950 (201.0)	2,890 (327.0)	2,720 (166.0)	3,080 (86.6)	3,080 (90.9)	3,340 (138.0)
Wire	2,970 (195.0)	3,270 (64.1)	3,530 (140.0)	2,930 (151.0)	2,760 (94.9)	3,000 (69.5)	2,990 (152.0)	2,930 (82.5)	2,810 (72.4)	3,050 (117.0)	3,070 (160.0)	3,180 (165.0)
600 Freeness[3]												
Low pressure (40 lb/in.^{2})												
Blotter	1,470 (67.0)	1,800 (77.6)	2,050 (59.4)	1,470 (56.0)	1,530 (53.0)	1,890 (53.4)	[4]1,480 (76.8)	[4]1,480 (76.8)	[4]1,480 (76.8)	1,660 (51.2)	1,370 (104.0)	1,460 (55.6)
Wire	1,490 (49.5)	1,730 (60.6)	2,210 (69.2)	1,570 (46.3)	1,510 (36.6)	1,750 (86.7)	[4]1,350 (80.9)	[4]1,350 (80.9)	[4]1,350 (80.9)	1,630 (79.7)	1,410 (69.4)	1,480 (85.8)
High pressure (160 lb/in.^{2})												
Blotter	2,480 (114.0)	2,740 (163.0)	3,100 (71.0)	2,150 (137.0)	2,050 (93.1)	2,370 (103.0)	[4]2,350 (138.0)	[4]2,350 (138.0)	[4]2,350 (138.0)	2,420 (47.6)	2,230 (94.8)	2,180 (66.5)
Wire	2,500 (44.7)	2,710 (130.0)	3,140 (136.0)	2,390 (154.0)	2,290 (202.0)	2,720 (89.3)	[4]2,240 (146.0)	[4]2,240 (146.0)	[4]2,240 (146.0)	2,550 (59.1)	2,280 (79.0)	2,220 (94.7)

[1] Numbers in parentheses are standard deviation.
[2] Percent consistency.
[3] Canadian Standard, ml.
[4] Pulps not refined (CSF was below 600 after fiberizing).

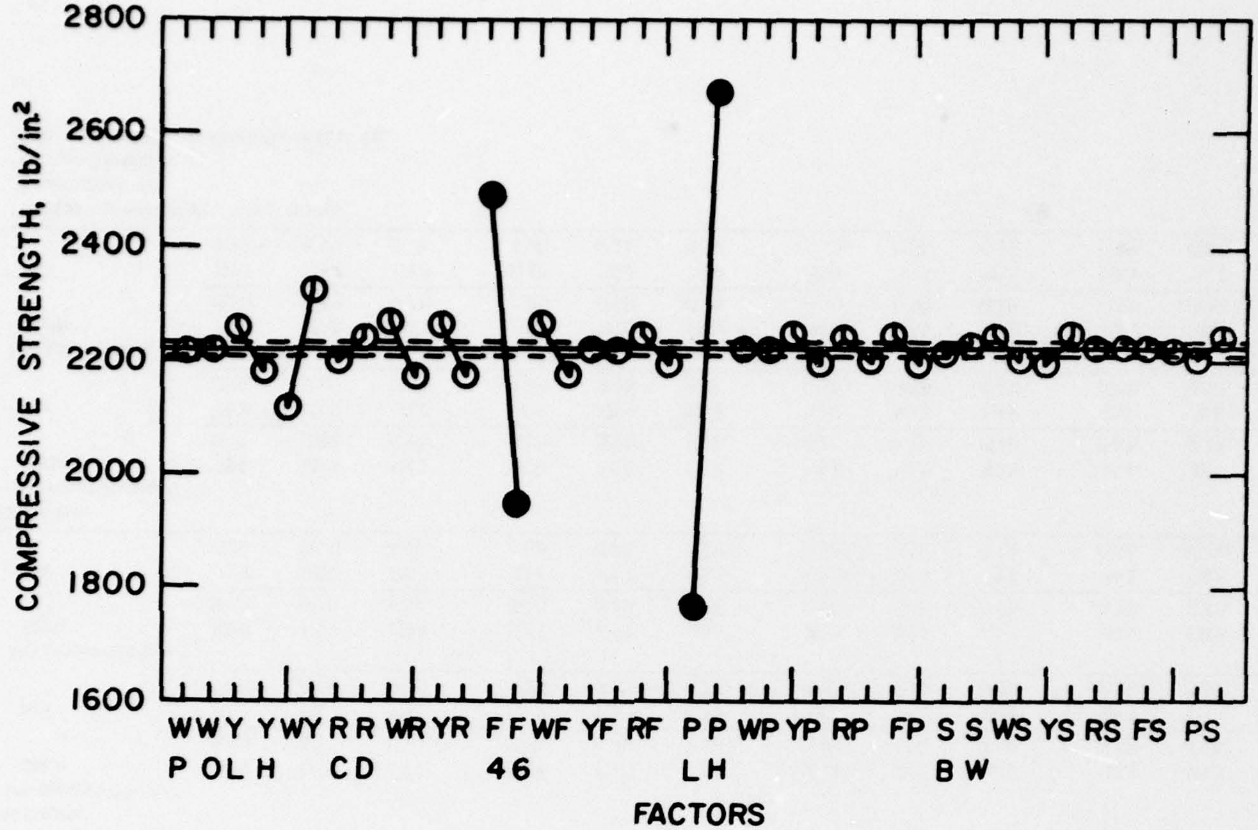

Figure 2.—Effect of various factors on the compressive strength of 42-lb/M ft² handsheets. The significant factors are freeness (F) and wet-press pressure (P) and are indicated by the filled symbols. (Factor identification as for fig. 1.)

(M 146 576)

Table 5.—Ring crush strength (lb) of 42-lb/M ft² handsheets[1]

	Southern pine kraft						Red oak kraft					
	Low yield (49.3 pct)			High yield (60.2 pct)			Low yield (50.8 pct)			High yield (60.9 pct)		
	Conical refiner	Double disk refiner		Conical refiner	Double disk refiner		Conical refiner	Double disk refiner		Conical refiner	Double disk refiner	
	[2]3	[2]3	[2]18	[2]3	[2]3	[2]18	[2]3	[2]3	[2]20	[2]3	[2]3	[2]20
450 Freeness[3]												
Low pressure (40 lb/in.²)												
Blotter	115.6	117.2	135.4	123.0	121.0	133.5	104.4	108.7	102.2	112.9	121.1	126.6
	(6.62)	(6.72)	(7.82)	(7.23)	(6.04)	(8.06)	(3.90)	(6.26)	(4.45)	(4.72)	(4.33)	(5.93)
Wire	118.3	131.2	129.7	122.7	119.7	127.0	99.0	108.6	102.7	107.9	117.5	129.6
	(7.63)	(4.76)	(8.19)	(6.12)	(4.35)	(8.78)	(4.06)	(6.13)	(3.99)	(9.14)	(4.65)	(3.13)
High pressure (160 lb/in.²)												
Blotter	121.9	119.7	120.9	113.9	126.1	116.5	122.3	122.2	115.1	130.4	133.0	136.6
	(6.92)	(9.74)	(7.50)	(8.77)	(4.83)	(4.70)	(5.87)	(5.76)	(7.00)	(7.32)	(5.81)	(3.95)
Wire	111.8	121.7	120.0	111.6	124.3	119.2	118.2	124.3	122.6	116.5	125.5	126.5
	(8.25)	(6.53)	(4.01)	(13.9)	(8.60)	(5.83)	(9.32)	(4.11)	(6.15)	(5.93)	(13.00)	(12.00)
600 Freeness[3]												
Low pressure (40 lb/in.²)												
Blotter	79.6	103.5	114.1	98.6	102.1	115.4	[4]68.5	[4]68.5	[4]68.5	96.7	83.4	94.8
	(5.95)	(3.08)	(6.53)	(3.13)	(5.37)	(3.31)	(6.21)	(6.21)	(6.21)	(5.69)	(2.74)	(3.46)
Wire	96.9	104.0	116.7	100.9	103.4	115.8	[4]69.8	[4]69.8	[4]69.8	90.5	85.8	89.1
	(3.16)	(2.87)	(4.98)	(7.29)	(3.38)	(6.17)	(3.33)	(3.33)	(3.33)	(7.76)	(8.13)	(6.22)
High pressure (160 lb/in.²)												
Blotter	118.5	122.5	132.1	113.4	119.9	125.9	[4]87.5	[4]87.5	[4]87.5	119.9	100.1	106.4
	(4.24)	(7.07)	(7.73)	(7.35)	(3.68)	(4.30)	(6.50)	(6.50)	(6.50)	(3.93)	(3.96)	(8.43)
Wire	111.1	115.3	118.3	113.2	123.2	125.3	[4]93.4	[4]93.4	[4]93.4	114.4	104.2	111.1
	(8.79)	(4.93)	(3.23)	(6.17)	(7.23)	(4.24)	(3.53)	(3.53)	(3.53)	(7.69)	(6.84)	(10.70)

[1] Numbers in parentheses are standard deviation.
[2] Percent consistency.
[3] Canadian Standard, ml.
[4] Pulps not refined (CSF was below 600 after fiberizing).

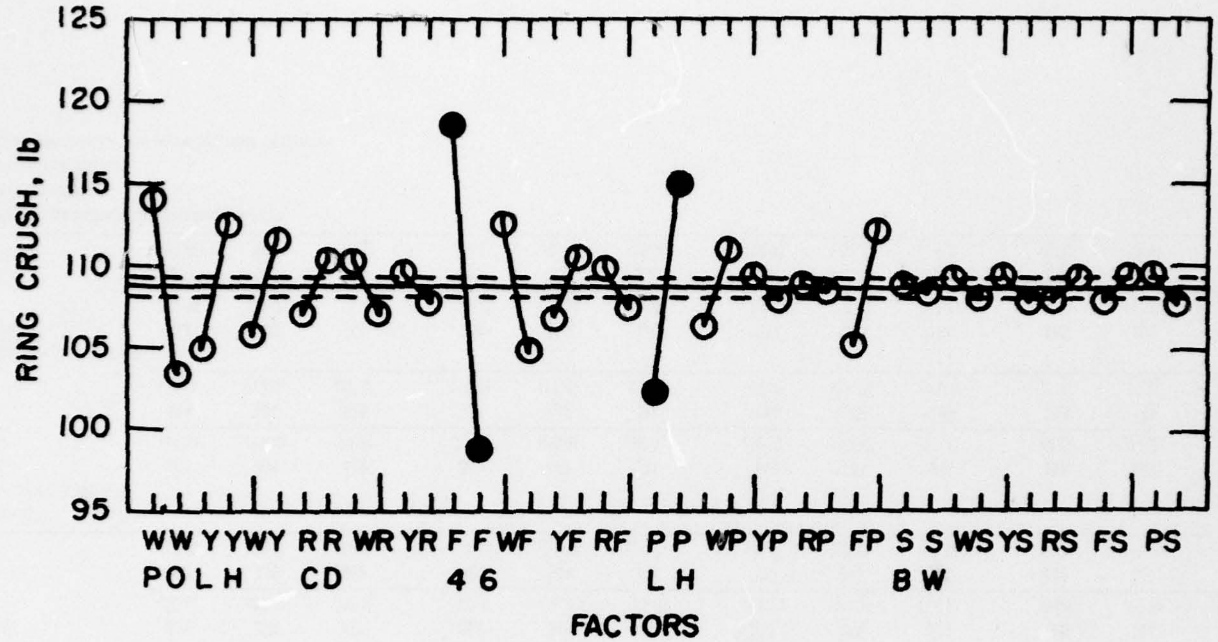

Figure 3.—Effect of various factors on the ring crush strength of 42-lb/M ft² handsheets. The significant factors are freeness (F) and wet-press pressure (P) and are indicated by the filled symbols. (Factor identification as for fig. 1.)

(M 146 575)

Table 6.—Tear strength (g) of 42-lb/M ft² handsheets[1]

	Southern pine kraft						Red oak kraft					
	Low yield (49.3 pct)			High yield (60.2 pct)			Low yield (50.8 pct)			High yield (60.9 pct)		
	Conical refiner	Double disk refiner		Conical refiner	Double disk refiner		Conical refiner	Double disk refiner		Conical refiner	Double disk refiner	
	[2]3	[2]3	[2]18	[2]3	[2]3	[2]18	[2]3	[2]3	[2]20	[2]3	[2]3	[2]20
450 Freeness[3]												
Low pressure (40 lb/in.²)												
Blotter	367 (16.3)	386 (13.3)	402 (15.4)	289 (13.5)	347 (13.0)	345 (16.9)	207 (11.8)	216 (17.6)	204 (19.3)	170 (5.4)	167 (8.6)	192 (11.0)
Wire	383 (25.4)	385 (13.3)	398 (30.0)	275 (12.0)	338 (16.6)	329 (15.4)	212 (11.2)	200 (12.4)	211 (14.7)	180 (8.6)	172 (15.2)	200 (19.7)
High pressure (160 lb/in.²)												
Blotter	331 (15.5)	358 (21.7)	377 (22.5)	268 (17.3)	308 (9.3)	301 (16.3)	221 (17.1)	244 (23.5)	220 (10.8)	165 (5.4)	184 (17.6)	188 (13.8)
Wire	332 (13.8)	339 (23.2)	366 (21.6)	260 (27.9)	304 (21.7)	304 (10.7)	231 (20.5)	243 (11.5)	231 (15.3)	162 (7.4)	172 (10.2)	196 (11.0)
600 Freeness[3]												
Low pressure (40 lb/in.²)												
Blotter	387 (12.2)	400 (10.0)	419 (21.8)	305 (22.4)	341 (20.6)	347 (22.1)	[4]143 (10.7)	[4]143 (10.7)	[4]143 (10.7)	158 (7.8)	141 (11.2)	141 (9.4)
Wire	384 (13.6)	404 (17.0)	415 (22.6)	301 (15.9)	332 (17.4)	338 (11.4)	[4]149 (18.3)	[4]149 (18.3)	[4]149 (18.3)	153 (7.4)	144 (9.3)	139 (8.6)
High pressure (160 lb/in.²)												
Blotter	362 (16.5)	362 (11.2)	353 (14.3)	280 (15.3)	312 (11.9)	310 (4.2)	[4]163 (13.6)	[4]163 (13.6)	[4]163 (13.6)	165 (9.4)	161 (11.0)	161 (7.9)
Wire	339 (13.6)	344 (11.9)	344 (14.2)	266 (10.1)	302 (9.1)	300 (15.8)	[4]196 (24.2)	[4]196 (24.2)	[4]196 (24.2)	167 (6.7)	162 (9.3)	162 (6.7)

[1] Numbers in parentheses are standard deviation.
[2] Percent consistency.
[3] Canadian Standard, ml.
[4] Pulps not refined (CSF was below 600 after fiberizing).

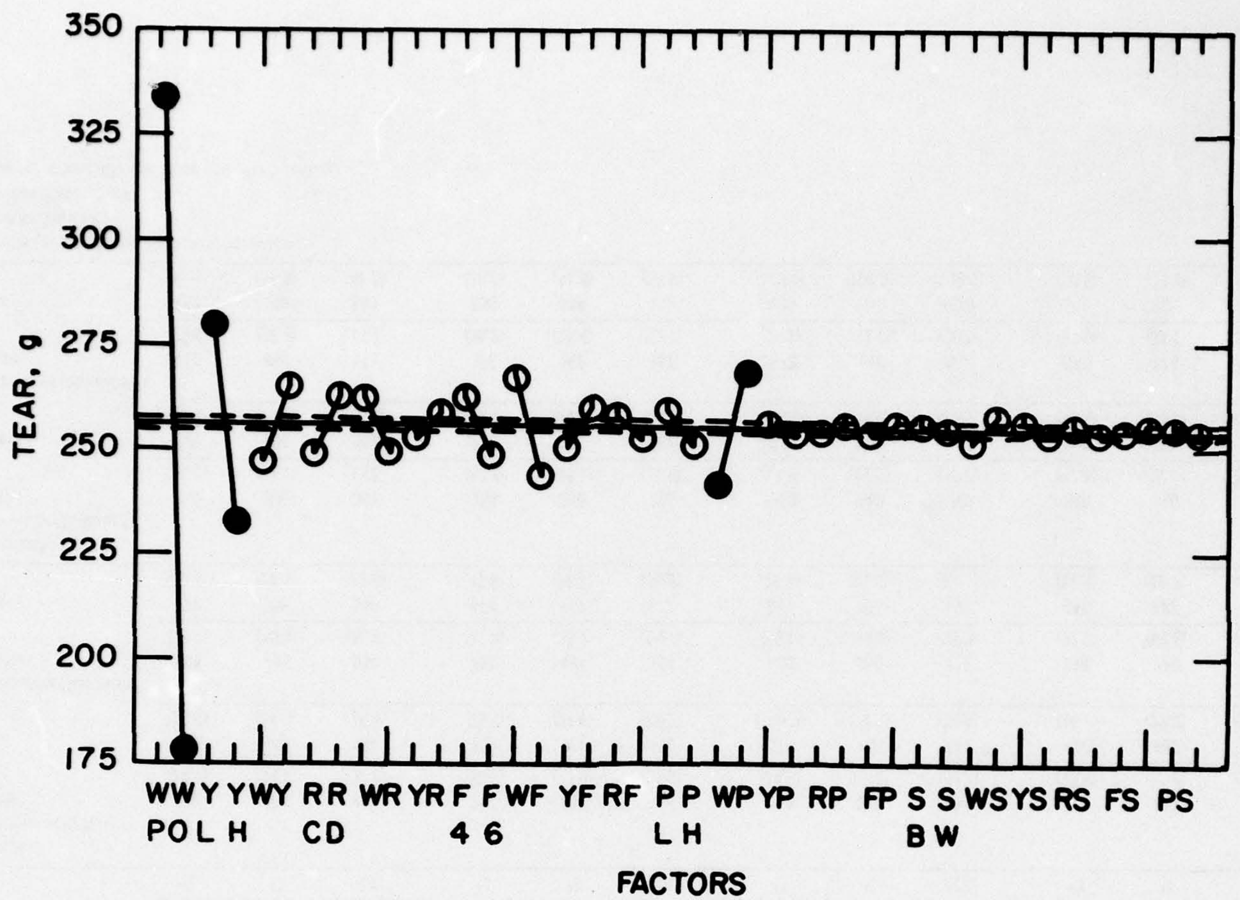

Figure 4.—Effect of various factors on the tear strength of 42-lb/M ft² handsheets. The significant factors are wood species (W), yield (Y), and the wood-pressure (WP) interaction and are indicated by the filled symbols. (Factor identification as for fig. 1.)

(M 146 574)

Table 7.—Modulus of elasticity (ksi) of 42-lb/M ft[2] handsheets[1]

	Southern pine kraft						Red oak kraft					
	Low yield (49.3 pct)			High yield (60.2 pct)			Low yield (50.8 pct)			High yield (60.9 pct)		
	Conical refiner	Double disk refiner		Conical refiner	Double disk refiner		Conical refiner	Double disk refiner		Conical refiner	Double disk refiner	
	[2]3	[2]3	[2]18	[2]3	[2]3	[2]18	[2]3	[2]3	[2]20	[2]3	[2]3	[2]20
450 Freeness[3]												
Low pressure (40 lb/in.[2])												
Blotter	362 (24.7)	441 (49.8)	431 (32.8)	281 (33.2)	308 (23.0)	396 (22.0)	452 (16.5)	512 (61.3)	482 (60.8)	480 (15.9)	444 (21.8)	538 (38.6)
Wire	332 (50.5)	440 (24.8)	486 (36.8)	283 (25.1)	321 (24.6)	410 (60.2)	518 (106.0)	461 (27.8)	489 (34.9)	440 (16.2)	480 (93.2)	474 (34.9)
High pressure (160 lb/in.[2])												
Blotter	553 (37.1)	595 (40.4)	554 (95.8)	454 (37.8)	434 (35.2)	494 (59.7)	800 (45.1)	650 (44.5)	722 (81.3)	694 (92.3)	735 (69.6)	680 (42.5)
Wire	577 (29.7)	598 (27.4)	570 (72.6)	474 (38.6)	421 (26.7)	517 (56.5)	683 (26.6)	754 (82.0)	692 (87.1)	647 (52.8)	622 (60.3)	670 (38.4)
600 Freeness[3]												
Low pressure (40 lb/in.[2])												
Blotter	266 (16.7)	306 (21.1)	364 (13.5)	258 (40.8)	230 (15.1)	296 (11.0)	[4]368 (17.3)	[4]368 (17.3)	[4]368 (17.3)	368 (32.2)	380 (27.9)	359 (50.0)
Wire	278 (12.4)	334 (26.3)	363 (30.6)	244 (17.4)	239 (16.6)	267 (23.0)	[4]434 (69.9)	[4]434 (69.9)	[4]434 (69.9)	370 (15.9)	359 (40.6)	328 (19.1)
High pressure (160 lb/in.[2])												
Blotter	442 (25.6)	496 (28.1)	541 (14.1)	376 (38.2)	362 (25.8)	381 (22.7)	[4]578 (30.1)	[4]578 (30.1)	[4]578 (30.1)	557 (50.4)	546 (54.1)	468 (24.9)
Wire	452 (47.4)	500 (55.5)	550 (48.5)	436 (28.6)	394 (41.8)	432 (30.5)	[4]619 (108.0)	[4]619 (108.0)	[4]619 (108.0)	559 (16.5)	485 (39.0)	477 (24.2)

[1] Numbers in parentheses are standard deviation.
[2] Percent consistency.
[3] Canadian Standard, ml.
[4] Pulps not refined (CSF was below 600 after fiberizing).

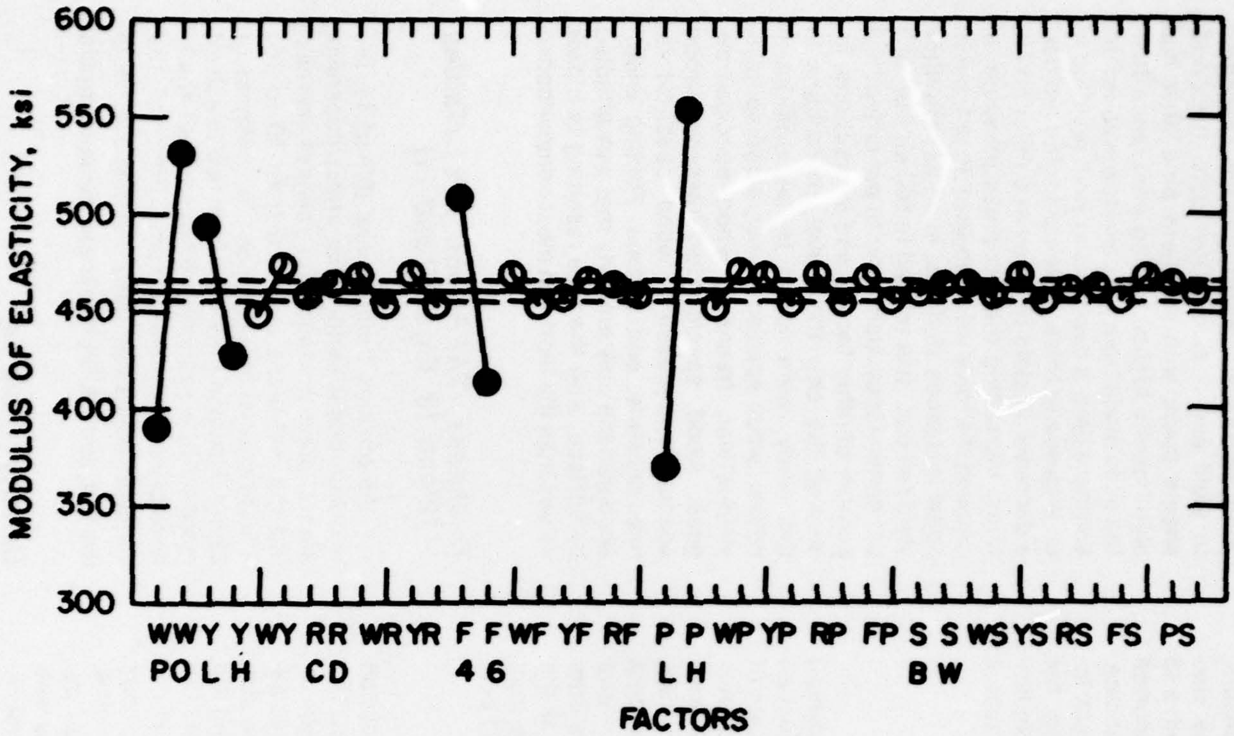

Figure 5.—Effect of various factors on the MOE of 42-lb/M ft² handsheets. The significant factors are wood species (W), yield (Y), freeness (F), and wet-press pressure (P) and are indicated by the filled symbols. (Factor identification as for fig. 1.) (M 146 573)

Tensile Strength (lb/in.²) (Table 8, Fig. 6)

The results indicate that four factors and one interaction affect the tensile strength: species, yield, freeness, pressure, and the species-yield interaction. The wet-press pressure was the most significant: a 48 pct increase in tensile strength occurred with an increase in wet-press pressure. Reducing freeness resulted in a 30 pct increase. With southern pine, lowering the yield resulted in a significant increase in tensile strength, but with red oak there was a reduction in tensile strength (table 8).

Tensile Strain to Failure (Table 9, Fig. 7)

Freeness, species, and the interaction between species and yield had significant effects on tensile strain to failure. The type of wood fiber had a 60 pct effect, but the presence of the interaction with yield indicates that yield is important depending on species. Results indicate that, in general, handsheets made from low-yield southern pine have greater strain to failure than those made from high yield, whereas for short-fiber red oak the reverse is true. As the CSF was reduced from 600 to 450 ml the strain was increased 17 pct.

Burst (Table 10, Fig. 8)

Four factors and one interaction significantly affected the burst strength. The four factors were: species, yield, freeness, and pressure. The interaction was species-yield. Changing from southern pine to oak resulted in a reduction in burst. Reducing the yield resulted in an increase in burst for the handsheets made from southern pine but the reverse was true for the handsheets made from red oak in most of the comparisons. As was expected, as the freeness was decreased, the burst increased, and as the wet-press pressure was increased, the burst increased.

Folds (Table 11, Fig. 9)

The property of fold is characterized by a number of factors and interactions, the most significant ones being the wood species, yield, wet-press pressure, and the interaction of yield and species. Obviously, the handsheets made with southern pine fiber had significantly higher folding endurance than the ones made from red oak. However, for the southern pine, a decrease in yield resulted in an increase in folds, whereas for the red oak, a decrease in yield resulted in a reduction in folds. Increasing the wet-press pressure increased the folds an average of 30 pct, but in some instances 10 times, such as with high-yield red oak, disk refined to 600 ml CSF at 3 pct consistency. Using the 10 pct criterion, a number of other factors and interactions, including the only three-level interactions in the study, were found to be significant: refiner, wood species-refiner, wood species-yield-refiner, freeness, wood species-freeness, wood species-yield-freeness, wood species-yield-pressure, wood species-freeness-pressure, and surface. Folding endurance was the only property that was affected by surface, with the wire resulting in higher values than the blotter in most comparisons.

Thickness (TAPPI and FPL) (Tables 12 and 13, Figs. 10 and 11)

As obvious from figures 10 and 11, the two significant factors that affect thickness are wet-press pressure and freeness. Increasing the wet-press pressure from 40 to 160 lb/in.² resulted in a decrease in thickness of 22 pct. Reducing the CSF from 600 to 450 ml resulted in a reduction of handsheet thickness of approximately 10 pct. Effect of the variables was essentially the same on both the FPL and TAPPI thickness measurements.

Density (Table 14)

The density of the various handsheets is given in table 14.

SUMMARY

Considering the data in terms of papermaking combinations that result in handsheets with high strength properties, the following emerged. Low-yield, southern pine pulp, refined in a disk mill at 3 pct consistency to 450 ml CSF and formed using high wet-press pressure, was of approximately equal quality—depending on which properties are considered the most important—as the low-yield, southern pine pulp, refined in a disk mill at 18 pct consistency to 600 ml CSF and formed using high wet-press pressure. If tear is not important, the handsheets made from high-yield red oak, refined with a disk refiner at 20 pct consistency to 450 ml CSF and formed using high wet-press pressure, had surprisingly good properties. These red oak sheets, in fact, were better than the handsheets made with high-yield southern pine except for tear, burst, and tensile strain to failure.

Table 8.—Tensile strength (lb/in.^{2}) of 42-lb/M ft^2 handsheets[1]

	Southern pine kraft						Red oak kraft					
	Low yield (49.3 pct)			High yield (60.2 pct)			Low yield (50.8 pct)			High yield (60.9 pct)		
	Conical refiner	Double disk refiner		Conical refiner	Double disk refiner		Conical refiner	Double disk refiner		Conical refiner	Double disk refiner	
	[2]3	[2]3	[2]18	[2]3	[2]3	[2]18	[2]3	[2]3	[2]20	[2]3	[2]3	[2]20
450 Freeness[3]												
Low pressure (40 lb/in.^{2})												
Blotter	4,930 (256)	5,690 (560)	5,960 (222)	3,440 (197)	3,710 (184)	4,550 (195)	3,720 (173)	4,120 (401)	3,730 (141)	4,160 (127)	4,160 (149)	4,580 (447)
Wire	4,550 (341)	5,820 (364)	6,160 (429)	3,560 (173)	3,980 (179)	5,080 (515)	3,940 (736)	3,770 (318)	3,870 (411)	4,100 (85)	4,490 (444)	4,740 (293)
High pressure (160 lb/in.^{2})												
Blotter	7,280 (419)	8,360 (162)	8,470 (395)	5,530 (680)	5,720 (286)	6,160 (629)	6,910 (759)	6,330 (245)	6,380 (455)	6,340 (485)	6,840 (215)	7,220 (334)
Wire	7,740 (425)	8,740 (609)	8,310 (267)	6,048 (187)	5,230 (912)	6,660 (93)	7,230 (609)	7,070 (935)	6,580 (289)	6,720 (476)	6,590 (222)	7,570 (309)
600 Freeness[3]												
Low pressure (40 lb/in.^{2})												
Blotter	3,440 (115)	4,370 (154)	4,840 (205)	2,930 (271)	2,930 (147)	3,670 (119)	[4]2,430 (120)	[4]2,430 (120)	[4]2,430 (120)	2,790 (77)	2,420 (143)	2,940 (185)
Wire	3,480 (137)	4,470 (279)	4,940 (315)	3,220 (108)	3,030 (169)	3,520 (48)	[4]2,570 (115)	[4]2,570 (115)	[4]2,570 (115)	3,140 (78)	2,420 (99)	2,670 (94)
High pressure (160 lb/in.^{2})												
Blotter	5,630 (416)	6,940 (223)	7,180 (302)	4,670 (195)	4,430 (457)	4,850 (244)	[4]4,540 (395)	[4]4,540 (395)	[4]4,540 (395)	4,830 (240)	4,270 (165)	4,230 (231)
Wire	5,970 (632)	7,500 (253)	8,120 (850)	5,520 (531)	4,880 (218)	5,630 (249)	[4]4,490 (623)	[4]4,490 (623)	[4]4,490 (623)	5,280 (328)	4,540 (297)	4,510 (130)

[1] Numbers in parentheses are standard deviation.
[2] Percent consistency.
[3] Canadian Standard, ml.
[4] Pulps not refined (CSF was below 600 after fiberizing).

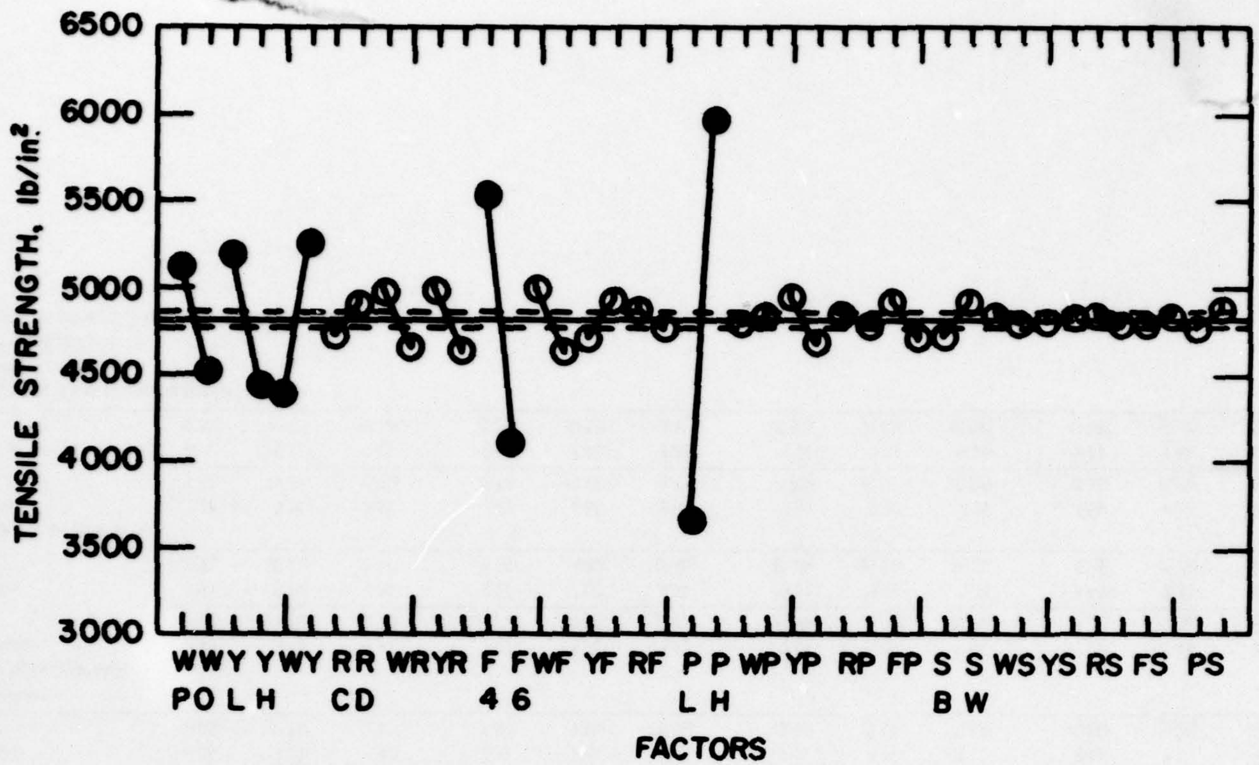

Figure 6.—Effect of various factors on the tensile strength of 42-lb/M ft² handsheets. The significant factors are wood species (W), yield (Y), freeness (F), wet-press pressure (P), and the wood species-yield (WY) interaction and are indicated by the filled symbols. (Factor identification as for fig. 1.)

(M 146 569)

Table 9.—Tensile strain to failure (pct) of 42-lb/M ft² handsheets[1]

	Southern pine kraft						Red oak kraft					
	Low yield (49.3 pct)			High yield (60.2 pct)			Low yield (50.8 pct)			High yield (60.9 pct)		
	Conical refiner	Double disk refiner		Conical refiner	Double disk refiner		Conical refiner	Double disk refiner		Conical refiner	Double disk refiner	
	[2]3	[2]3	[2]18	[2]3	[2]3	[2]18	[2]3	[2]3	[2]20	[2]3	[2]3	[2]20
450 Freeness[3]												
Low pressure (40 lb/in.²)												
Blotter	9.35 (0.53)	8.42 (0.56)	11.00 (0.83)	7.75 (1.38)	7.03 (0.83)	8.88 (0.30)	4.58 (0.33)	4.22 (0.38)	4.23 (0.32)	5.15 (0.40)	4.84 (0.32)	5.49 (0.28)
Wire	9.46 (0.72)	9.10 (0.36)	10.97 (1.06)	7.88 (1.11)	8.08 (0.60)	9.43 (0.44)	3.72 (0.80)	4.45 (0.51)	4.05 (0.55)	5.33 (0.58)	5.28 (0.28)	5.78 (0.26)
High pressure (160 lb/in.²)												
Blotter	9.03 (0.46)	8.87 (0.63)	11.45 (0.35)	6.85 (2.02)	7.81 (0.27)	9.19 (0.80)	4.40 (0.93)	5.10 (0.23)	4.64 (0.38)	5.77 (0.38)	5.41 (0.38)	6.21 (0.50)
Wire	9.56 (0.60)	9.39 (0.44)	11.60 (0.41)	9.23 (0.97)	7.25 (1.89)	10.76 (0.59)	5.30 (0.56)	4.74 (0.49)	5.17 (0.33)	6.11 (0.26)	5.65 (0.28)	6.78 (0.38)
600 Freeness[3]												
Low pressure (40 lb/in.²)												
Blotter	7.85 (0.42)	8.16 (0.28)	8.92 (0.34)	7.07 (1.22)	6.75 (0.82)	8.41 (0.41)	[4]2.91 (0.30)	[4]2.91 (0.30)	[4]2.91 (0.30)	3.79 (0.38)	3.45 (0.33)	3.93 (0.23)
Wire	7.97 (0.36)	8.18 (0.41)	9.00 (0.48)	8.52 (0.56)	7.22 (0.85)	8.29 (0.46)	[4]3.04 (0.14)	[4]3.04 (0.14)	[4]3.04 (0.14)	4.44 (0.34)	3.82 (0.21)	3.83 (0.38)
High pressure (160 lb/in.²)												
Blotter	7.28 (0.81)	8.10 (0.20)	9.35 (0.66)	7.49 (0.44)	6.84 (1.27)	8.05 (0.72)	[4]3.39 (0.57)	[4]3.39 (0.57)	[4]3.39 (0.57)	4.56 (0.36)	4.23 (0.28)	4.10 (0.53)
Wire	8.05 (0.61)	8.30 (0.47)	9.48 (0.42)	8.32 (1.25)	7.20 (0.53)	8.87 (0.41)	[4]3.09 (0.61)	[4]3.09 (0.61)	[4]3.09 (0.61)	5.07 (0.48)	4.43 (0.32)	4.73 (0.25)

[1] Numbers in parentheses are standard deviation.
[2] Percent consistency.
[3] Canadian Standard, ml.
[4] Pulps not refined (CSF was below 600 after fiberizing).

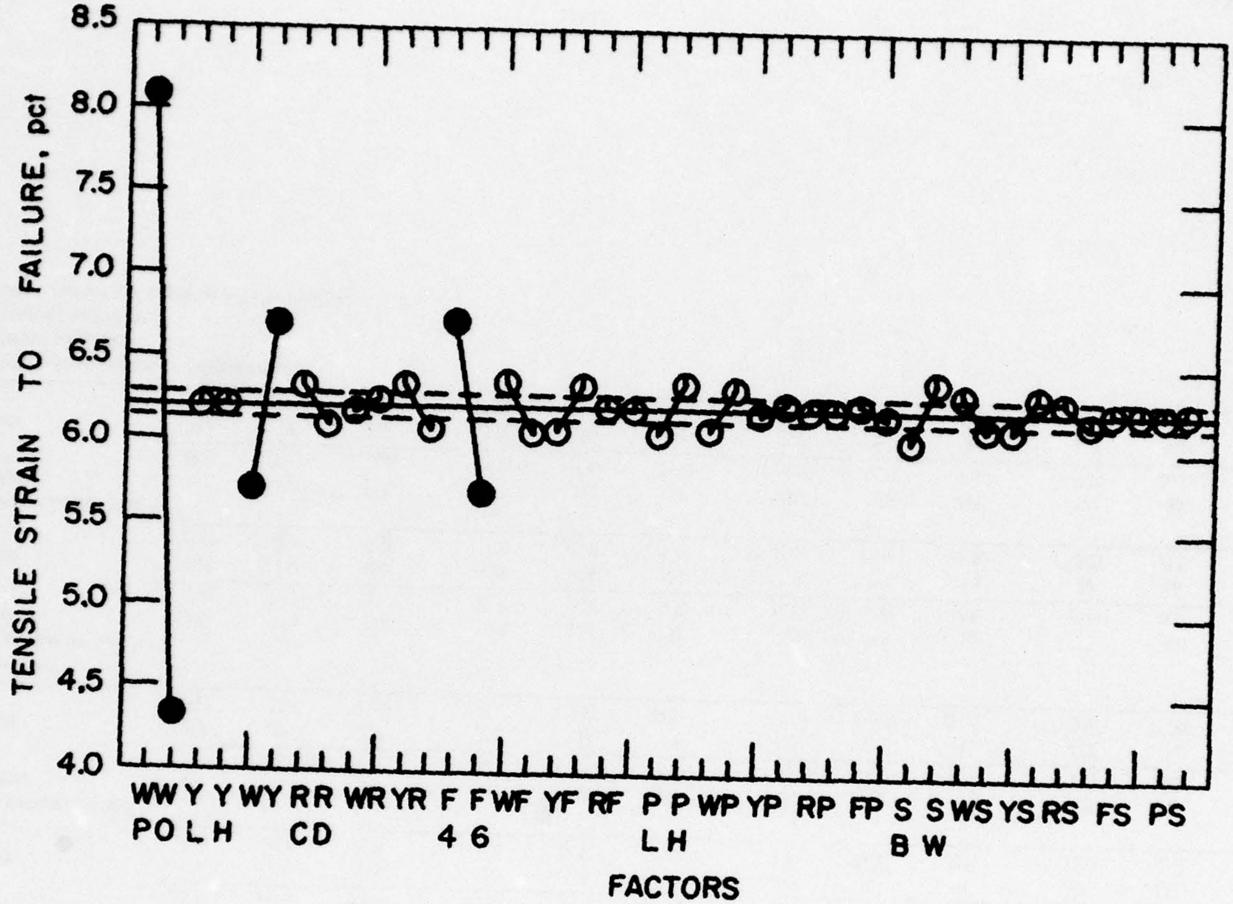

Figure 7.—Effect of various factors on the tensile strain to failure of a 42-lb/M ft² handsheet. The significant factors are wood species (W), freeness (F), and the wood species-yield (WY) interaction and are indicated by the filled symbols. (Factor identification as for fig. (M 146 579)

Table 10.—Burst strength (pt) of 42-lb/M ft² handsheets[1]

	Southern pine kraft						Red oak kraft					
	Low yield (49.3 pct)			High yield (60.2 pct)			Low yield (50.8 pct)			High yield (60.9 pct)		
	Conical refiner	Double disk refiner		Conical refiner	Double disk refiner		Conical refiner	Double disk refiner		Conical refiner	Double disk refiner	
	[2]3	[2]3	[2]18	[2]3	[2]3	[2]18	[2]3	[2]3	[2]20	[2]3	[2]3	[2]20
450 Freeness[3]												
Low pressure (40 lb/in.²)												
Blotter	169 (6.7)	184 (11.0)	200 (10.0)	128 (7.1)	138 (10.0)	143 (8.2)	100 (6.2)	91 (4.7)	89 (6.6)	100 (4.3)	107 (7.5)	117 (6.6)
Wire	175 (8.9)	198 (11.0)	205 (9.5)	124 (9.3)	136 (8.4)	150 (7.8)	102 (7.7)	101 (8.4)	94 (9.2)	97 (11.0)	112 (8.1)	116 (6.6)
High pressure (160 lb/in.²)												
Blotter	200 (11.0)	213 (10.0)	215 (11.0)	149 (12.0)	148 (12.0)	162 (9.7)	136 (11.0)	128 (7.5)	122 (7.6)	129 (5.1)	141 (9.9)	152 (6.2)
Wire	207 (8.6)	221 (12.0)	227 (11.0)	152 (9.1)	167 (9.9)	172 (9.7)	155 (14.0)	138 (13.0)	140 (11.0)	133 (9.9)	156 (17.0)	162 (9.2)
600 Freeness[3]												
Low pressure (40 lb/in.²)												
Blotter	136 (8.8)	169 (9.3)	169 (9.3)	124 (8.5)	121 (8.9)	132 (6.4)	[4]55 (2.8)	[4]55 (2.8)	[4]55 (2.8)	72 (5.6)	62 (2.5)	71 (3.5)
Wire	143 (7.6)	167 (8.1)	180 (7.5)	125 (7.7)	126 (5.3)	129 (8.1)	[4]59 (2.6)	[4]59 (2.6)	[4]59 (2.6)	80 (5.2)	66 (3.6)	69 (3.2)
High pressure (160 lb/in.²)												
Blotter	162 (9.8)	192 (13.0)	200 (12.0)	142 (4.8)	142 (7.4)	148 (13.0)	[4]85 (8.1)	[4]85 (8.1)	[4]85 (8.1)	103 (7.6)	85 (6.3)	94 (6.8)
Wire	182 (8.9)	199 (11.0)	207 (9.2)	152 (12.0)	156 (12.0)	164 (8.7)	[4]93 (7.5)	[4]93 (7.5)	[4]93 (7.5)	118 (5.8)	100 (8.3)	106 (6.1)

[1] Numbers in parentheses are standard deviation.
[2] Percent consistency.
[3] Canadian Standard, ml.
[4] Pulps not refined (CSF was below 600 after fiberizing).

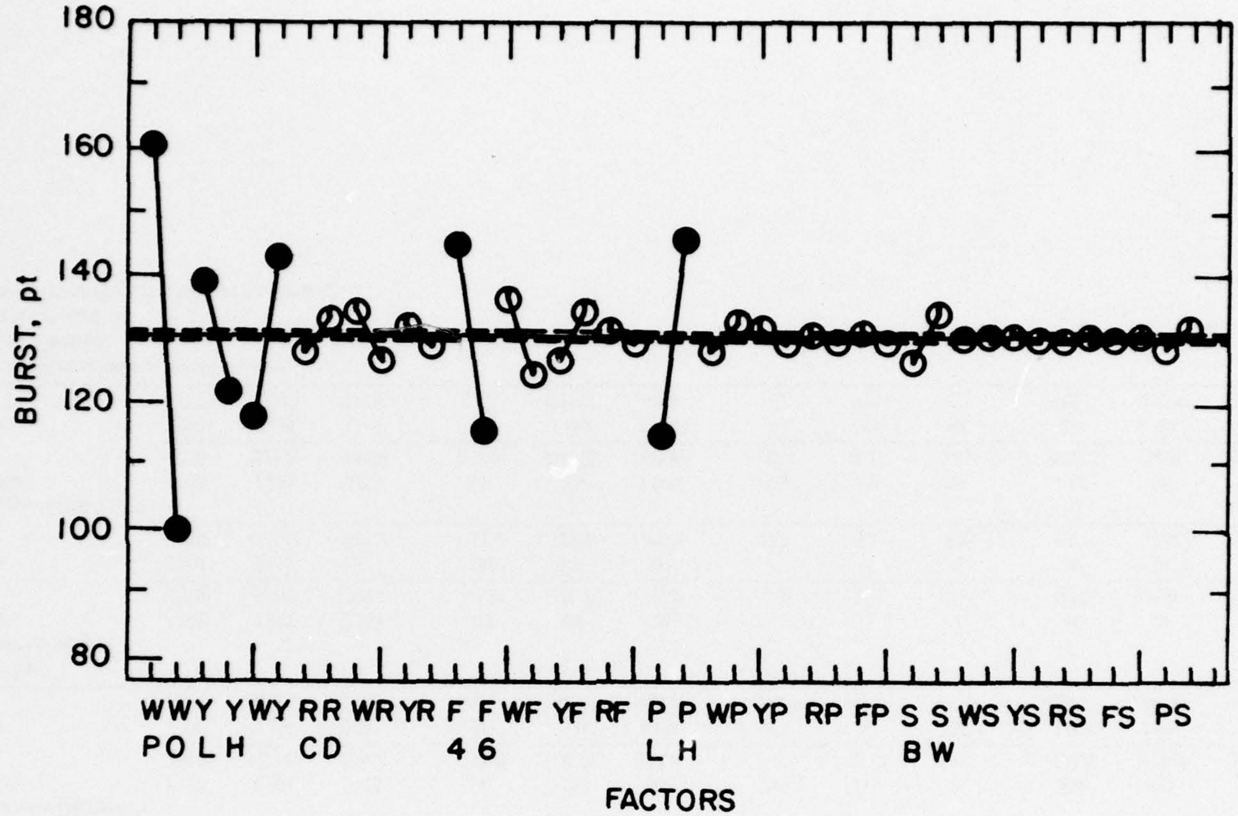

Figure 8.—Effect of various factors on the burst strength of 42-lb/M ft² handsheets. The significant factors are wood species (W), yield (Y), freeness (F), wet-press pressure (P), and the wood species-yield (WY) interaction and are indicated by the filled symbols. (Factor identification as for fig. 1.)

(M 146 570)

Table 11.—Folding endurance of 42-lb/M ft² handsheets[1]

	Southern pine kraft						Red oak kraft					
	Low yield (49.3 pct)			High yield (60.2 pct)			Low yield (50.8 pct)			High yield (60.9 pct)		
	Conical refiner	Double disk refiner		Conical refiner	Double disk refiner		Conical refiner	Double disk refiner		Conical refiner	Double disk refiner	
	[2]3	[2]3	[2]18	[2]3	[2]3	[2]18	[2]3	[2]3	[2]20	[2]3	[2]3	[2]20
450 Freeness[3]												
Low pressure (40 lb/in.²)												
Blotter	1,845	2,886	2,049	696	1,045	1,085	59	28	30	230	164	447
	(438.0)	(475.0)	(413.0)	(83.6)	(206.0)	(137.0)	(11.7)	(4.3)	(3.3)	(71.9)	(29.3)	(92.6)
Wire	2,135	2,764	1,941	644	1,099	963	73	46	53	314	309	661
	(166.0)	(435.0)	(161.0)	(117.0)	(116.0)	(219.0)	(14.3)	(9.8)	(14.6)	(89.4)	(120.0)	(242.0)
High pressure (160 lb/in.²)												
Blotter	2,132	2,364	2,452	681	1,090	962	260	139	126	854	862	965
	(234.0)	(432.0)	(576.0)	(134.0)	(146.0)	(194.0)	(77.7)	(37.3)	(45.0)	(274.0)	(229.0)	(148.0)
Wire	2,332	2,934	2,886	902	1,134	1,180	469	263	285	1,209	1,501	1,857
	(245.0)	(432.0)	(211.0)	(169.0)	(85.6)	(488.0)	(143.0)	(49.9)	(72.0)	(306.0)	(261.0)	(430.0)
600 Freeness[3]												
Low pressure (40 lb/in.²)												
Blotter	1,681	2,145	2,153	712	878	884	[4]7	[4]7	[4]7	56	24	44
	(266.0)	(621.0)	(308.0)	(53.7)	(134.0)	(139.0)	(1.1)	(1.1)	(1.1)	(10.8)	(4.3)	(12.5)
Wire	1,880	2,536	2,617	807	914	922	[4]9	[4]9	[4]9	59	36	38
	(209.0)	(236.0)	(448.0)	(269.0)	(109.0)	(165.0)	(3.7)	(3.7)	(3.7)	(16.7)	(6.9)	(11.7)
High pressure (160 lb/in.²)												
Blotter	2,333	2,733	3,065	838	966	1,075	[4]29	[4]29	[4]29	364	247	235
	(422.0)	(524.0)	(423.0)	(194.0)	(282.0)	(142.0)	(6.4)	(6.4)	(6.4)	(128.0)	(61.3)	(55.2)
Wire	2,247	3,105	3,390	976	1,183	1,276	[4]48	[4]48	[4]48	574	364	414
	(330.0)	(552.0)	(243.0)	(57.7)	(327.0)	(241.0)	(7.2)	(7.2)	(7.2)	(165.0)	(112.0)	(121.0)

[1] Numbers in parentheses are standard deviation.
[2] Percent consistency.
[3] Canadian Standard, ml.
[4] Pulps not refined (CSF was below 600 after fiberizing).

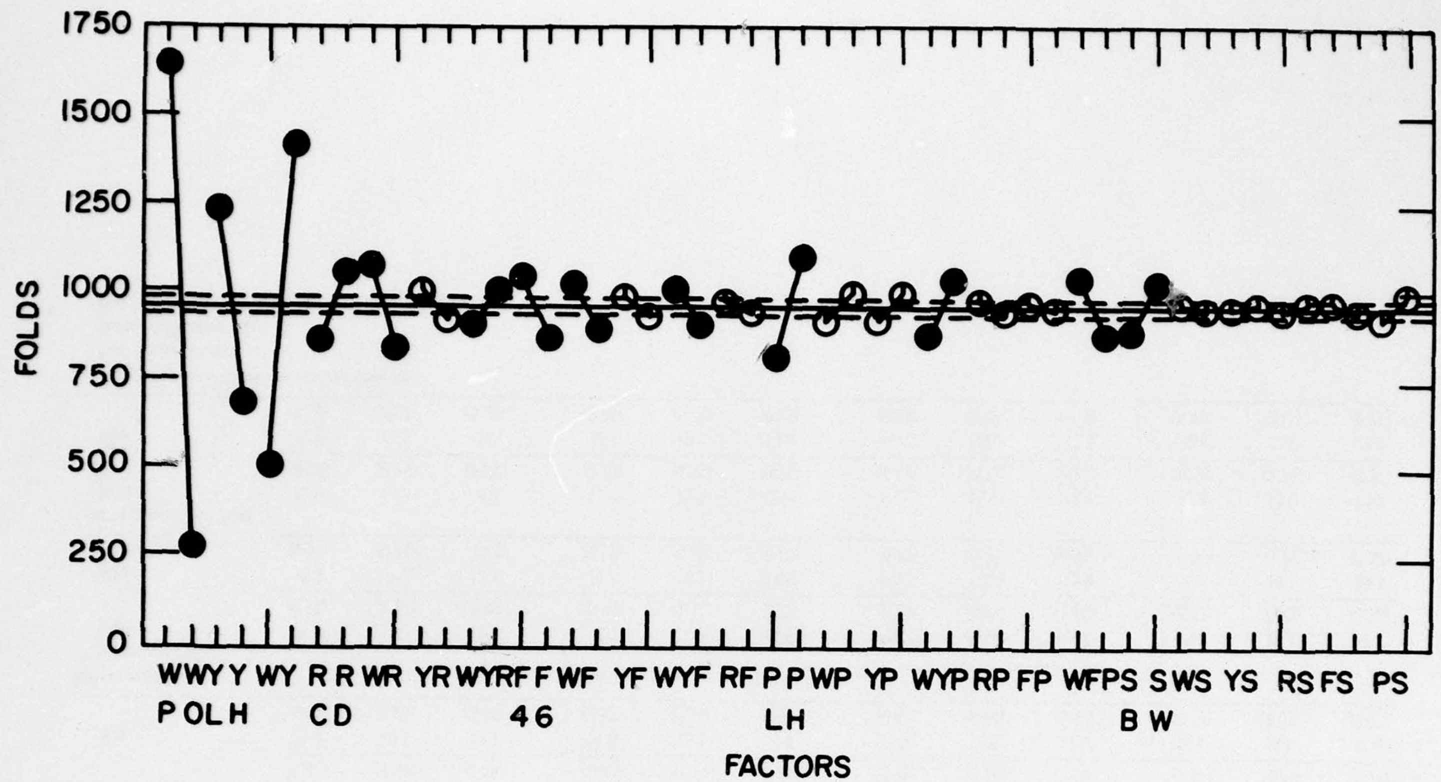

Figure 9.—Effect of various factors on the folding endurance of 42-lb/M ft² handsheets. The four most significant factors are wood species (W), yield (Y), pressure (P), and the wood species-yield (WY) interaction and are indicated by the filled symbols. (Factor identification as for fig. 1.)

(M 146 578)

Table 12.—TAPPI thickness (mil) of 42-lb/M ft² handsheets[1]

	Southern pine kraft						Red oak kraft					
	Low yield (49.3 pct)			High yield (60.2 pct)			Low yield (50.8 pct)			High yield (60.9 pct)		
	Conical refiner	Double disk refiner		Conical refiner	Double disk refiner		Conical refiner	Double disk refiner		Conical refiner	Double disk refiner	
	[2]3	[2]3	[2]18	[2]3	[2]3	[2]18	[2]3	[2]3	[2]20	[2]3	[2]3	[2]20
450 Freeness[3]												
Low pressure (40 lb/in.²)												
Blotter	13.1 (0.37)	12.7 (0.21)	11.7 (0.47)	14.5 (0.25)	14.6 (0.44)	13.1 (0.38)	14.6 (0.14)	14.8 (0.34)	15.2 (0.52)	14.4 (0.41)	14.3 (0.44)	13.9 (0.41)
Wire	13.7 (0.45)	12.7 (0.23)	11.8 (0.30)	14.9 (0.57)	14.2 (0.24)	13.2 (0.36)	14.4 (0.62)	14.6 (0.32)	14.5 (0.28)	14.2 (0.17)	13.9 (0.27)	13.7 (0.21)
High pressure (160 lb/in.²)												
Blotter	11.0 (0.35)	10.5 (0.24)	10.4 (0.46)	12.1 (0.39)	12.2 (0.28)	11.3 (0.21)	11.2 (0.20)	11.5 (0.14)	11.4 (0.19)	12.4 (0.59)	11.6 (0.34)	11.5 (0.34)
Wire	11.0 (0.40)	10.5 (0.25)	10.2 (0.18)	11.9 (0.52)	11.8 (0.33)	11.4 (0.37)	11.7 (0.42)	11.5 (0.14)	11.4 (0.40)	11.9 (0.28)	11.5 (0.29)	11.9 (0.46)
600 Freeness[3]												
Low pressure (40 lb/in.²)												
Blotter	16.5 (0.74)	13.7 (0.20)	13.2 (0.58)	16.1 (0.46)	16.3 (0.38)	14.5 (0.23)	[4]16.4 (0.29)	[4]16.4 (0.29)	[4]16.4 (0.29)	15.5 (0.37)	16.4 (0.25)	16.2 (0.28)
Wire	15.8 (0.64)	14.8 (0.31)	13.1 (0.52)	15.6 (0.56)	16.7 (0.55)	14.6 (0.19)	[4]15.9 (0.30)	[4]15.9 (0.30)	[4]15.9 (0.30)	15.3 (0.50)	16.1 (0.30)	15.8 (0.32)
High pressure (160 lb/in.²)												
Blotter	11.6 (0.25)	11.3 (0.25)	10.8 (0.35)	13.2 (0.20)	13.5 (0.35)	12.4 (0.26)	[4]12.3 (0.13)	[4]12.3 (0.13)	[4]12.3 (0.13)	12.6 (0.53)	13.0 (0.35)	13.2 (0.30)
Wire	12.2 (0.36)	11.5 (0.24)	10.6 (0.20)	12.2 (0.26)	12.5 (0.22)	11.6 (0.25)	[4]12.5 (0.29)	[4]12.5 (0.29)	[4]12.5 (0.29)	12.4 (0.25)	12.9 (0.19)	13.2 (0.27)

[1] *Numbers in parentheses are standard deviation.*
[2] Percent consistency.
[3] Canadian Standard, ml.
[4] Pulps not refined (CSF was below 600 after fiberizing).

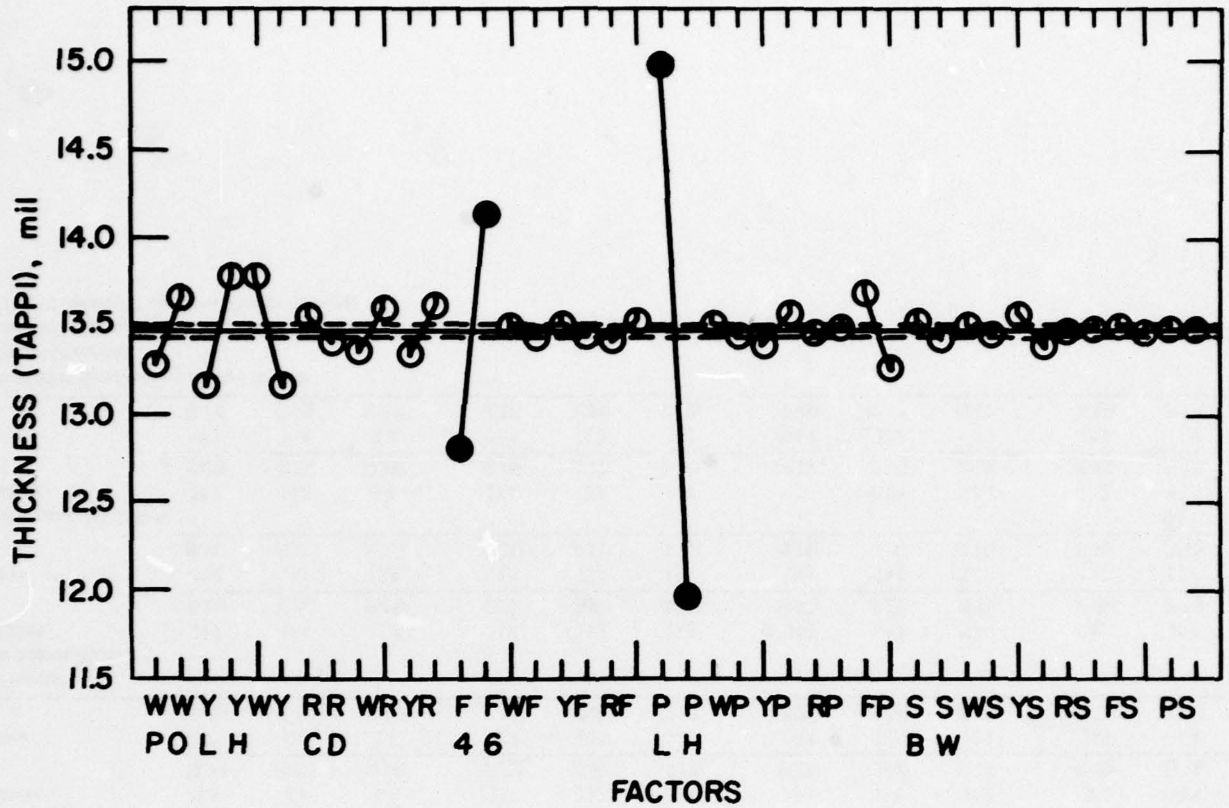

Figure 10.—Effect of various factors on the TAPPI thickness of 42-lb/M ft² handsheets. The significant factors are freeness (F) and wet-press pressure (P) and are indicated by the filled symbols. (Factor identification as for fig. 1.)
(M 146 571)

Table 13.—FPL thickness (mil) of 42-lb/M ft² handsheets[1]

	Southern pine kraft						Red oak kraft					
	Low yield (49.3 pct)			High yield (60.2 pct)			Low yield (50.8 pct)			High yield (60.9 pct)		
	Conical refiner	Double disk refiner		Conical refiner	Double disk refiner		Conical refiner	Double disk refiner		Conical refiner	Double disk refiner	
	[2]3	[2]3	[2]18	[2]3	[2]3	[2]18	[2]3	[2]3	[2]20	[2]3	[2]3	[2]20
450 Freeness[3]												
Low pressure (40 lb/in.²)												
Blotter	12.5 (0.17)	11.8 (0.32)	10.2 (0.22)	14.1 (0.60)	13.9 (0.40)	12.1 (0.15)	13.5 (0.31)	13.9 (0.16)	13.5 (0.22)	12.9 (0.13)	12.9 (0.29)	12.6 (0.40)
Wire	12.9 (0.37)	11.5 (0.16)	10.3 (0.21)	13.3 (0.27)	13.8 (0.32)	11.7 (0.34)	13.4 (0.26)	13.7 (0.21)	13.5 (0.33)	12.5 (0.22)	13.2 (0.14)	12.3 (0.15)
High pressure (160 lb/in.²)												
Blotter	9.6 (0.30)	9.4 (0.22)	8.7 (0.14)	11.0 (0.35)	11.3 (0.30)	10.4 (0.23)	10.4 (0.10)	11.0 (0.09)	10.6 (0.19)	10.2 (0.10)	10.5 (0.14)	10.1 (0.24)
Wire	9.7 (0.23)	9.2 (0.11)	9.2 (0.16)	10.4 (0.22)	10.5 (0.21)	10.2 (0.33)	10.4 (0.21)	10.5 (0.09)	10.9 (0.26)	10.2 (0.17)	10.4 (0.06)	10.1 (0.13)
600 Freeness[3]												
Low pressure (40 lb/in.²)												
Blotter	14.7 (0.24)	13.4 (0.21)	12.3 (0.24)	15.0 (0.55)	15.8 (0.27)	13.9 (0.20)	[4]14.8 (0.27)	[4]14.8 (0.27)	[4]14.8 (0.27)	14.7 (0.05)	15.3 (0.26)	14.6 (0.10)
Wire	14.2 (0.36)	13.4 (0.32)	12.0 (0.31)	14.4 (0.21)	15.4 (0.21)	14.1 (0.19)	[4]14.6 (0.16)	[4]14.6 (0.16)	[4]14.6 (0.16)	13.7 (0.50)	15.4 (0.34)	14.3 (0.21)
High pressure (160 lb/in.²)												
Blotter	10.7 (0.23)	10.6 (0.15)	9.4 (0.14)	12.1 (0.39)	12.8 (0.23)	11.8 (0.30)	[4]11.3 (0.18)	[4]11.3 (0.18)	[4]11.3 (0.18)	11.2 (0.10)	11.7 (0.19)	11.7 (0.05)
Wire	10.3 (0.18)	10.4 (0.19)	9.8 (0.19)	11.1 (0.32)	11.8 (0.32)	10.8 (0.20)	[4]11.2 (0.18)	[4]11.2 (0.18)	[4]11.2 (0.18)	10.9 (0.31)	11.5 (0.15)	11.4 (0.17)

[1] Numbers in parentheses are standard deviation.
[2] Percent Consistency.
[3] Canadian Standard, ml.
[4] Pulps not refined (CSF was below 600 after fiberizing).

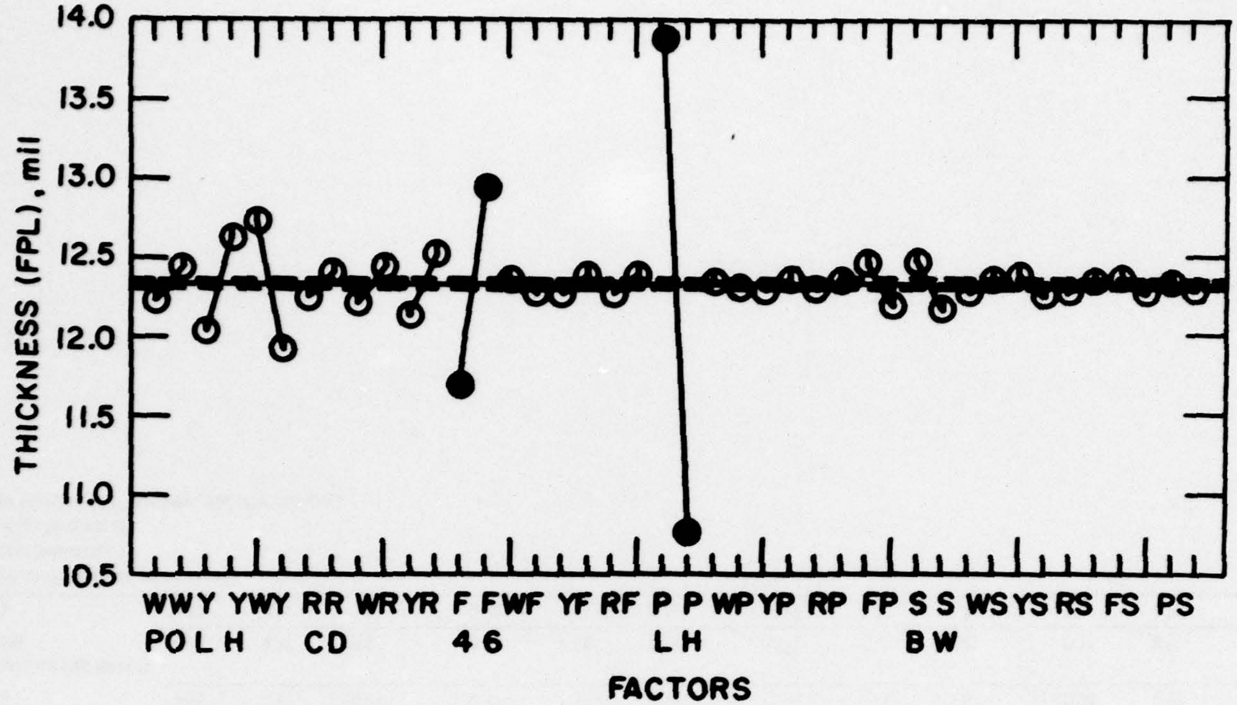

Figure 11.—Effect of various factors on the FPL thickness of 42-lb/M ft² handsheets. The significant factors are freeness (F) and wet-press pressure (P) and are indicated by the filled symbols. (Factor identification as for fig. 1.) (M 146 572)

Table 14.—Density (g/cc) of 42-lb/M ft^2 handsheets[1]

	Southern pine kraft						Red oak kraft					
	Low yield (49.3 pct)			High yield (60.2 pct)			Low yield (50.8 pct)			High yield (60.9 pct)		
	Conical refiner	Double disk refiner		Conical refiner	Double disk refiner		Conical refiner	Double disk refiner		Conical refiner	Double disk refiner	
	[2]3	[2]3	[2]18	[2]3	[2]3	[2]18	[2]3	[2]3	[2]20	[2]3	[2]3	[2]20
450 Freeness[3]												
Low pressure (40 lb/in.^{2})												
Blotter	0.64	0.66	0.76	0.58	0.58	0.68	0.60	0.60	0.60	0.66	0.63	0.66
Wire	0.63	0.69	0.76	0.60	0.60	0.69	0.62	0.59	0.61	0.65	0.62	0.68
High pressure (160 lb/in.^{2})												
Blotter	0.83	0.84	0.91	0.76	0.71	0.81	0.79	0.75	0.78	0.78	0.79	0.81
Wire	0.87	0.88	0.89	0.77	0.73	0.83	0.80	0.77	0.77	0.80	0.77	0.81
600 Freeness[3]												
Low pressure (40 lb/in.^{2})												
Blotter	0.56	0.58	0.66	0.55	0.51	0.57	[4]0.54	[4]0.54	[4]0.54	0.56	0.54	0.56
Wire	0.55	0.59	0.66	0.57	0.51	0.57	[4]0.54	[4]0.54	[4]0.54	0.60	0.53	0.56
High pressure (160 lb/in.^{2})												
Blotter	0.76	0.77	0.82	0.68	0.65	0.70	[4]0.71	[4]0.71	[4]0.71	0.73	0.69	0.71
Wire	0.77	0.81	0.85	0.76	0.67	0.74	[4]0.72	[4]0.72	[4]0.72	0.74	0.71	0.72

[1] Based on FPL thickness measurements.
[2] Percent consistency.
[3] Canadian Standard, ml.
[4] Pulps not refined (CSF was below 600 after fiberizing).

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32 p. (Research Paper FPL 323)

Factors considered include wood species, pulp yield, type of refiner, pulp consistency, amount of refining, wet-press pressure, and surface.

KEYWORDS: Linerboard, papermaking, property interactions, strength.

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